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A NEW TYPE OF DC SUPERCONDUCTING FAULT CURRENT LIMITER

Ziqiang Wei, Ying Xin, Wei Hong, Chao Yang, Jianxi Lan and Quan Li

***Abstract*—A new type Superconducting Fault Current Limiter (SFCL) for dc applications is proposed. This SFCL consists of a current transmission/limiting coil, an iron-core, and a set of superconductor rings. The superconductor rings are placed between the current transmission/limiting coil and the iron-core. For application, the current transmission/limiting coil is connected in series to a dc transmission line. During normal power transmission, magnetic flux coupling between the current transmission/limiting coil and the iron-core is prevented by the magnetic shielding of the superconductor rings, and the current transmission coil has low impedance. Because of shielding effect of the superconductor rings iron core has high permeability at the beginning of short circuit, current limiting coil can effectively limit fault current rise. When the fault current reaches a certain level, the superconductor rings will quench and the shielding effect is greatly reduced. The current limiting coil strengthens the coupling with the iron core, increases the inductance, and will suppress the further increase of the fault current.**

A laboratory proof of concept prototype was made to demonstrate the feasibility of the idea. Experiments have been carried out with the prototype. In this presentation, we will introduce the detailed information of the principle, the prototype, and the experimental results. In addition a design of the new type DC SFCL is installed in a ±160kV HVDC system.

***Index Terms*—DC power system, Fault current, Magnetic shielding, and SFCL Superconducting Fault-Current Limiters**

I. INTRODUCTION

ZERO resistance and Meissner effect(perfect diamagnetism) of superconductor provide significant advantages in power system application. High current density of superconductive wires enables the realization of their application. [1-4]. Due to low resistance in normal operation of power grid, high resistance and short response time in fault limitation operation , SFCL (superconducting fault current limiter) can effectively limit the fault current, and play an important role in the electrical power system. Currently, the design and manufacture technology of SFCL is mature. Prototypes in operation network have been developed at home and abroad [5-7]. However, the SFCL technology is mainly used in AC network. Researches and studies of SFCL in DC systemare still in initial stage. According to the principle, several prototypes are developed, but there is no reports of practical case in network operation. [8-11].

VSC-HVDC (voltage source converter based high voltage direct current) technology doesn't induce reactive loss. This technology has low cost in circuit construction. It is also suitable for long-distant power supply, new energy resources connection and flexible interconnection of bulk power systems [12-13]. In the recent years, DC power grid develops rapidly and has a great prospect in China [14-15]. However, the limitation of component performance and topological structure of high-voltage direct current converter make it unable to resist short-circuit impact. The lack of zero crossing spot in DC fault current also makes it difficult for rapid malfunction cutoff. Meanwhile, compared with the alternating current system, fault current increases rapidly and significantly in VSC-HVDC, posing high requirements on maximum cutoff capacity and reaction speed of direct current breakers. These key issues are the technological difficulties that limit the development of the flexible HVDC system [16-18].

Superconducting direct current limitation is a feasible solution for the above problems. As DC power grid has different requirements on SFCL from AC power grid, SFCL should also be able to prevent the increase of fault current and sustained short-circuit current except rapid response, in order to achieve coordination between SFCL, direct current breakers and current converter[10-11]. In the case of steady operation for circuit, the SFCL cannot be influenced by excessively high electrical inductance. Hence, stable and low electrical inductance in normal operation, as well as current-limiting high electrical inductance are ideal performance of current limiter. Magnetic shielding type SFCL, which reacts fast and converts low inductance to high inductance when short circuit fault occurs, can be able to achieve these target [19-21].

II. PRINCIPLE OF MAGNETIC SHIELDING TYPE SFCL AND PROTOTYPE

A. Principle of magnetic shielding type SFCL

Based on functional demands of DC power grid on fault limiter, and the operation principle of SFCL, this paper proposes a

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new solution of magnetic shielding type SFCL, which is shown in Fig 1. The current limiter consists of current transmission/ limiting coil, superconductor rings and closed iron core. Current transmission/ limiting coil can be superconducting inductance coil or traditional metal coil, which in series connection with electric transmission line. Superconductor rings is short-circuited coil. Current transmission/ limiting coil and superconductor rings are coaxially coupled to the closed iron core. When DC power line transmits electricity, due to the shielding effect of superconductor rings, coil inductance is quite low. At this point, current limiter is in low impedance. If short-circuit fault takes place, short-circuit current increases sharply, shielding effect of superconductor rings declines, inductance becomes high in current transmission/ limiting coil, and limiting short-circuit current.

The principle of current magnetic shielding type SFCL in ac power system is changing the shielding effect through the quench of superconductor rings to increase the current limiting inductance. However, in the dc system, there is an additional current limiting principle by using dc magnetic shielding type SFCL.

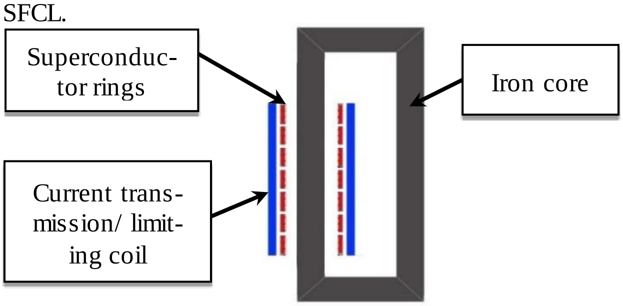

Fig. 1. Magnetic shielding type SFCL

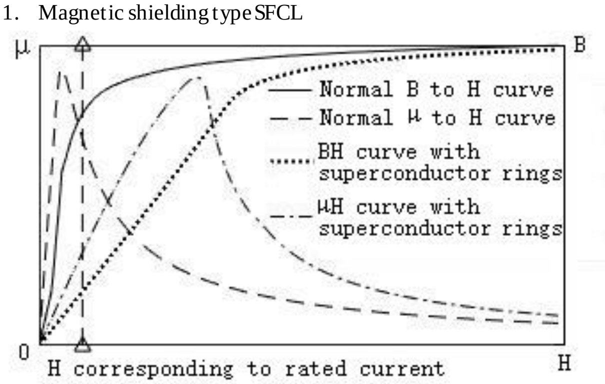

Fig. 2. Magnetic permeability curve of iron core, "μ" is magnetic permeability, "B" is magnetic flux density, "H" is magnetic field intensity

When current transmission/ limiting inductance coil is flux-coupling with iron core, the high magnetic conductivity of iron core can enhance inductance of the coil. As shown in Figure 2, when the dc rated current is in operation, the iron core is almost saturated, when the fault occurs, the iron core coil has no obvious advantages in enhancing the inductance in compare with the air core coil. However, in the case of adding superconductor rings, the shielding effect can allow the iron core remain in low magnetization state at the beginning, as shown in Fig. 2 –'H corresponding to rated current'. After the short circuit fault occurs, the permeability of iron core will increase to the maximum value and then reduced until the iron core reach the saturation. A high permeability will lead to a large inductance of the coil, which can obviously improve the current limiting effect. In additional, the superconductor rings can be seen as a short-circuited secondary side of coaxial transformer. When the superconductor rings quench after the short circuit fault, the superconductor rings will embody resistance, which may partly improve the current limiting effect. In the dc power system, the variation of permeability and resistance work together to affect the impedance of transmission/limiting coil. In the ac power system, there is zero crossing point in the transmission current, the permeability of iron core will spontaneously increase and reach the saturation without the superconductor rings. The variation of permeability has no positive effect on current limiting, only the variation of resistance in superconductor rings plays role in fault current limiting. Therefore, compared with the ac power system, the SFCL can embody a larger current limiting impedance in the dc power system, which lead to a better limiting effect. Through changing the number of superconductor rings and the number of turns of one ring, quenching threshold value can also be set with relevant line fault protection strategies.

This DC magnetic shielding type SFCL utilizes the zero resistivity effect and Meissner effect of superconductor. The zero resistivity effect allow the induced shielding current flowing without decay, the SFCL will embody low impedance in steady state and partly enlarged after quenching. On the other hand, the Meissner effect enable the magnetic shielding in the normal operation, during which the iron core remains in low magnetization state. When the fault occurs, the magnetic shielding effect will decrease, the permeability of iron core will become large and the inductance of transmission/limiting coil will be enhanced. This process do not exist in the application in ac power system. As a result, the magnetic shielding type SFCL is more suitable for the dc power system. μ

B. Experiment Prototype

TABLE I PARAMETERS OF THE EXPERIMENT PROTOTYPE

Superconductor rings	One ring height	12mm
	Inner diameter of rings	112mm
	One ring turns	2
	Number of rings	20
Current transmission/ limiting coil	Coil height	292mm
	Inner diameter of coil	128mm
	The coil turns	60
Iron core	Diameter of core column	48mm
	Core window width	129mm
	Core window height	474mm
	Yoke height	45mm

The experimental prototype is shown in Fig.3. There are twenty superconductor rings. Each superconductor ring is made of double-pancake shaped coils with the Bi2223 first generation of superconducting wires. Rings are wrapped on supporting barrel. There are twenty card slots to fixate each ring. Sixty turns of current transmission/ limiting coil are also manufactured by Bi2223 superconducting wires. The wire is 4mm wide and 0.22mm thick, and is calibrated with a critical current of 180A in self-fields. The critical current of superconductor rings and Current transmission/ limiting coil is tested about 160A. Iron core is made of silicon steel sheets with high

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magnetic permeability (reach to 7000～10000 H / m). The cryogenic container is epoxy resin bucket. Nonmetal container is used to avoid interruption in the experiment. Basic parameters of the prototype is shown in Table 1.

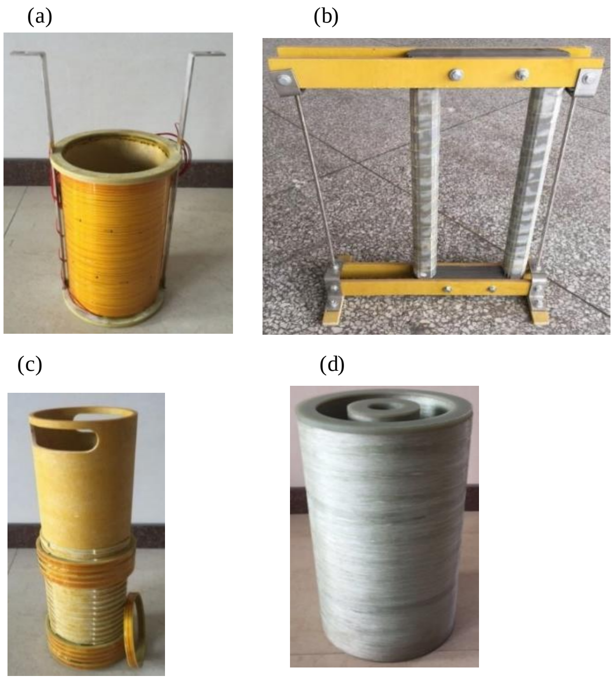

Fig. 3. Four parts of experiment prototype: (a) superconductor rings; (b) iron core; (c) current transmission/ limiting coil; (d) cryogenic container

III. Experiment and Analysis

A. Performance tests of prototype

The performance tests of SFCL prototype are conducted with 200A DC impulse current. Air core coil has fixed inductance of 0.16mH, 0.12mH, 0.08mH, 0.05mH with 0, 6, 12, 20 superconductor rings. The inductance of iron core coil varies with the current variation of current transmission/ limiting coil. The measured inductances of current transmission/ limiting coil in different conditions are shown in Fig 4. It indicates that, inductance decreases when the number of superconductor rings increases. The shielding effect enhance more with the increase of superconductor rings. The current corresponding to the maximum inductance increases with the increase of superconductor ring.

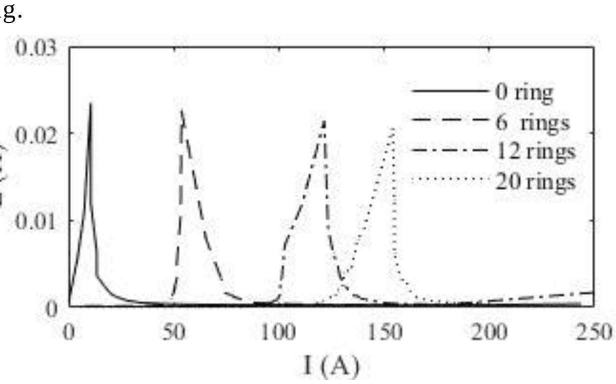

Fig. 4. Inductance of current transmission/ limiting coil

B. Current limiting tests

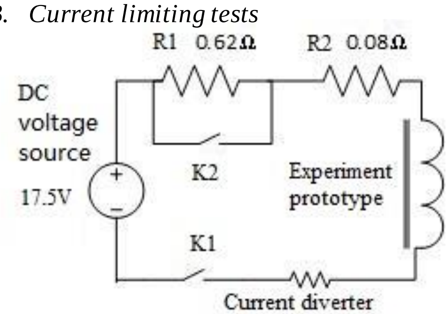

Fig. 5. Current limiting tests circuit

The test circuit is shown in Figure 5. R1 will be short connected at the time of 5ms after the limiting tests begin. The current changes from 25A to 220A in test without prototype. Impulse current test is conducted to the prototype. Electric current and voltage of current transmission/ limiting coil are recorded. Due to non-linear performance of iron core, electrical inductance of current transmission/ limiting inductance coil also indicate non-linear changes. The equation of electrical inductance and voltage $u = L * di/dt$ is used to calculate the inductance of current transmission/ limiting coil. The calculated inductance is the average inductance from the beginning of short circuit to the calculating time point.

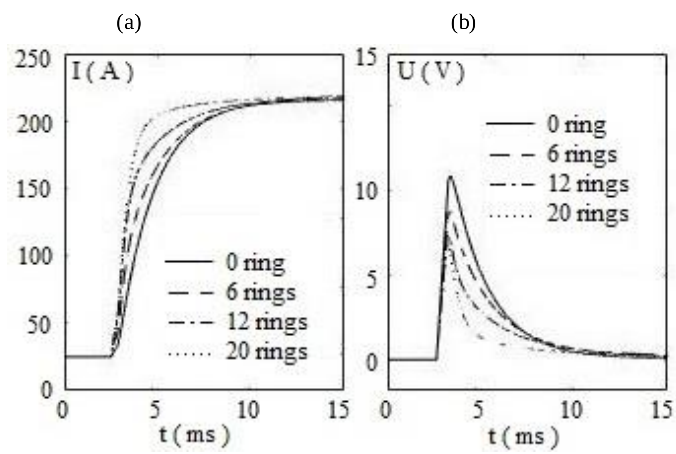

Fig. 6 Currents and voltages of experiment prototype in tests without iron core. (a) currents of current transmission/ limiting coil; (b) voltage of current transmission/ limiting coil

In the tests without iron core, the current limiting effect decreases with the increase of superconductor rings as shown in Fig. 6. The current limiting effect does not change monotonously with the increase of superconductor rings. As shown in Fig. 7 and Table II: at 10ms the current limiting effect of prototype with 6 superconductor rings is the strongest, and have biggest inductance; at 25ms the current limiting effect of prototype with 6 superconductor rings and 12 superconductor rings is almost identical, and prototype inductance with 12 superconductor rings is biggest. Because the shielding effect, at the beginning of short circuit the effect of current limiting with superconductor rings is poorer than without ring, but the current limiting effect will suddenly increase, which is because the superconductor rings' role of remaining the iron core in low magnetization state and the inductance of current transmission coil will increase rapidly after short circuit. The time of current limiting effect conversion can be defined as response time of the DC SFCL which is no more than 1 ms.

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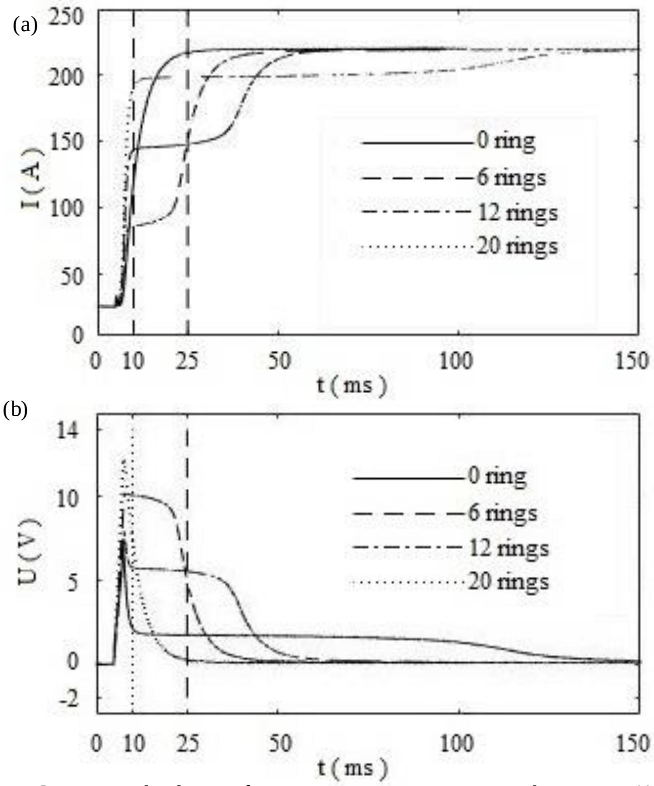

Fig. 7 Currents and voltages of experiment prototype in tests with iron core. (a) currents of current transmission/ limiting coil; (b) voltage of current transmission/ limiting coil

TABLE II CURRENT LIMITING TESTS RESULTS

N	L0 (mH)	LE	L1 (mH)	LE	L2 (mH)	LE
0	0.16	29.70%	0.389	45.80%	0.028	1.40%
6	0.12	24.00%	0.832	61.00%	0.802	31.30%
12	0.08	16.20%	0.247	34.70%	0.91	32.70%
20	0.06	0.112	0.065	0.131	0.204	0.098

In the table above, "N" is the number of superconductor rings; "L0" is the 10ms inductance of the test without iron core; "L1" is the 10ms inductance of the test with iron core; "L2" is the 25ms inductance of the test with iron core. The inductances are calculated from 5ms when the limiting tests begin. LE is the limiting effect.

IV. SIMULATION OF ±160KV HVDC SYSTEM

Taking the Nan' ao Island ±160kV MMC-HVDC system of China Southern Power Grid Company as a reference, the simulation system is constructed. This system is a four-terminal DC system with rated current of 1kA. Bipolar fault is the most serious short-circuit fault, which is used to simulate and verify the feasibility of DC SFCL. If there is no current limiting measure, the current rises sharply after short circuit as shown in Fig. 8, which exceeds the blocking current, and the DC system will be blocked. In addition, the short circuit current will rise to a very high level of 22kA, which will bring great pressure to the circuit breaker. In the Nan' ao Island ±160kV MMC-HVDC system, to prevent blockage of DC system, short circuit current should not exceed 3 times rated current within 2ms. Installation of a 500mH inductor will greatly slow down the current rise rate, will not exceed three times the rated current of 3kA, and the short-circuit current is also greatly limited, as shown in Fig. 8. But in normal operation of the HVDC system, adding such a large inductance may cause second-order oscillation with the circuit capacitance, which will affect the normal operation of the system. A 500mH air core inductor is large in size and expensive to fabricate.

A DC SFCL matching the HVDC system is designed and the basic parameters of the SFCL is shown in Table III. Both the superconductor rings and current transmission/ limiting coil are manufactured by superconducting wire. The superconductor rings should be manufactured by the second generation of superconducting wires, so that there are large resistance after quench. Air core inductance of current transmission/ limiting coil is only 14.3mH. In normal operation the inductance of the current transmission coil only about 10mH, with the shielding effect of superconductor rings. The current corresponding to the maximum inductance of the current transmission coil is about 2.4kA. This DC SFCL can achieve the same current limiting effect as 500 mH inductance when installed in the HVDC system as shown in Fig. 8. And the response time of the DC SFCL is no more than 1 ms

TABLE III PARAMETERS OF THE EXPERIMENT PROTOTYPE

Superconductor rings	One ring height	15.5mm
	Inner diameter of rings	1340mm
	One ring turns	14
	Number of rings	40
Current transmission/ limiting coil	Coil height	810mm
	Inner diameter of coil	1440mm
	The coil turns	100
Iron core	Diameter of core column	1000mm
	Core window width	1247mm
	Core window height	574mm
	Yoke height	785.4mm

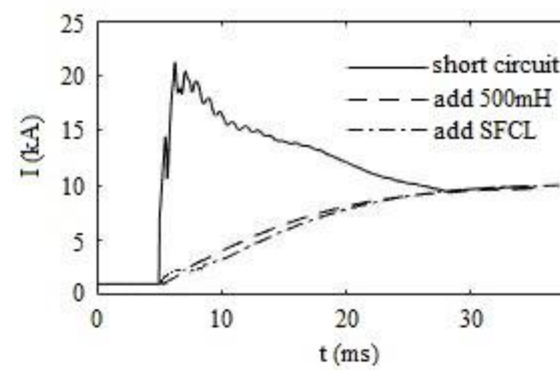

Fig. 8 Bipolar fault current of the ±160kV HVDC system. (a) without current limiting measure; (b) add 500mH current limiting inductor; (c) add the DC SFCL

V. CONCLUSION

Based on the experimental data and simulation, we can come to several summaries. The new type DC SFCL can display low inductance in normal operation and high inductance when short circuit occurs. Shielding effect of superconductor rings make the iron core in low magnetized state in normal operation, when short circuit fault occurs maximum permeability of iron core will be used and the current limiting inductance will be very large, which only works in DC systems not in AC system. The simulation in ±160kV HVDC system verifies feasibility of the new type DC SFCL.

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